Tracing the Origin of Galaxies in the Land of our Ancestors
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How do galaxies get their baryons?

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Abstract.
Understanding how galaxies obtain baryons, their stars and gas, over cosmic time is traditionally approached in two different ways - theoretically and observationally. In general, observational approaches to galaxy formation include measuring basic galaxy properties, such as luminosities, stellar masses, rotation speeds, star formation rates and how these features evolve through time. Theoretically, cosmologically based models collate the physical effects driving galaxy assembly - mergers of galaxies, accretion of gas, star formation, and feedback, amongst others, to form predictions which are matched to galaxy observables. An alternative approach is to examine directly, in an observational way, the processes driving galaxy assembly, including the effects of feedback. This is a new 'third way' towards understanding how galaxies are forming from gas accretion and mergers, and directly probes these effects instead of relying on simulations designed to reproduce observations. This empirical approach towards understanding galaxy formation, including the acquisition history of baryons, displays some significant differences with the latest galaxy formation models, in addition to directly demonstrating the mechanisms by which galaxies form most of their baryonic mass.

Keywords. Galaxy formation, galaxy evolution

1. Introduction

Galaxies are the astronomical gift that keeps on giving. Galaxies are used as locators of mass in the universe, where some of the best evidence for dark matter exists, and are used as tracers of distance in cosmological studies of the universe as a whole, providing us with the best evidence for dark energy. Galaxies themselves are however endlessly fascinating in themselves, as they are the basic structure of the universe. By understanding how and when galaxies formed and evolved we are essentially finding out how the universe itself is structured.

Many vigorous ongoing observational and theoretical programs are designed to answer the question of how galaxies form and evolve. Gravitational collapse is the obvious answer to this question, yet we know both theoretically and observationally that galaxies could not have the same total or stellar mass in the early universe as they do today. A collection of processes from mergers, gas accretion, and feedback from stars and AGN have all played a role in creating the universe of galaxies that we see today. We are however just starting to unravel the role of these various processes and how they work together.

Understanding galaxy formation in a physical way has traditionally been approached in a theoretical manner. The first attempts to understand galaxy formation, such as the collapse models of Eggen et al. (1962) have been based on observations of galaxy properties, such as the ages and velocities of stars in our own galaxy, to more modern attempts using quantities such as luminosity/mass functions in the local universe. However, all attempts to model galaxies with basic physics still cannot reproduce all known observations (e.g., Guo et al. 2010).

Contemporary approaches towards understanding galaxy formation in a theoretical and cosmological context are dominated by semi-analytical models which typically use local galaxy properties to calibrate their simulation output. The parameters adjusted in these simulations are many, and are based on initial conditions of baryons that are still unknown. Despite the immense effort over more than 30 years, these simulations still have significant problems in reproducing high redshift observations, particular for the most massive galaxies (e.g., Conselice et al. 2007; Bertone & Conselice 2009; Guo et al. 2010).

An alternative approach is to try to understand the various physical mechanisms that drive the formation of galaxies at high redshift, and to examine distant galaxies to directly trace these assembly processes on the evolution of the baryonic content of these systems. This is an empirical approach to galaxy evolution/formation, and its success requires that we are: (1) able to determine observationally the physical process driving evolution; and (2) be confident that we have identified all mechanisms in which galaxies obtain their baryons.

In this review, I will discuss the 'third way' of solving the problem of galaxy evolution in terms of their baryons. This method involves searching for physical processes of galaxy formation at high redshifts in galaxies as a function of their stellar mass, and determining the contribution of these processes to the further formation of the masses of galaxies at later times. By continuing this processes at all redshifts, where observations can reveal ongoing physical processes, we are measuring how galaxies are forming in a statistical sense as a function of galaxy mass.

For this 'third way' approach to work, it is necessary to be certain that we have identified the major processes by which galaxies form, and to have some confidence that we can identify these processes through observations. The first is easier to show – we are fairly certain that the dominant methods by which galaxies form are now identifiable. However, what is certainly not understood is the relative contributions of these various processes towards forming galaxies.

The processes that we believe to be dominant in settling baryons into galaxies and converting them into stars include: major and minor mergers, gas accretion, and gas cooling of residual gas from the initial collapse of the baryons and its dark matter halo. On the other hand, we now know that galaxy feedback, in the form of energy ejection, is a major process in regulating galaxy formation and evolution. This feedback can come in many forms including, and especially, feedback from stars, most prominently in the form of supernova, and feedback from energy emitted by a central massive AGN. Each of these processes in principle has an observational signature. In some cases, such as cooling of residual gas and gas accretion, direct signatures are difficult to find, however circumstantial evidence for these are obtainable.

Perhaps the most straightforward method that can be traced are major merger signatures, which can now be found using both galaxy pair and morphological methods (e.g,. Conselice et al. 2003, 2008) and through the kinematics of gas in these systems (e.g., Genzel et al. 2008). In general, it has been shown for typical galaxies of stellar masses 10^{9-10} $M_\odot$ that the total number of major mergers is roughly ~ 4 at $z < 3$ (Conselice et al. 2008). However, this amount of merging is not enough to account for the increase in the masses of galaxies during this epoch (Mortlock et al. 2011), and other formation processes are necessary.

Within this proceeding I will describe attempts to construct the baryonic assembly of galaxies using new data sets and programs focused on very massive galaxies with $M_\odot > 10^{11}$ $M_\odot$ at $z < 3$, including the *GOODS NICMOS Survey* (GNS).

2. Evolution of Massive Galaxies from the GOODS NICMOS Survey

Much of the data discussed henceforth originates from papers within the GOODS NICMOS Survey (GNS). This is a near-infrared survey of massive galaxies selected by $M_\odot > 10^{11}$ $M_\odot$ located at redshifts $1.5 < z < 3$. The depth of these images is $H_{\rm AB} = 26.8$ (5 σ), and the resolution is high enough to make basic morphological measurements, such as sizes and concentration (Buitrago et al. 2008; Conselice et al. 2010). This survey, combined with a lower redshift sample of similar mass galaxies from the POWIR/DEEP2 Survey (Conselice et al. 2007; Trujillo et al. 2007) allows us to trace galaxy formation processes for galaxies with masses $M_\odot > 10^{11}$ $M_\odot$ from $0.4 < z < 3$.

We primarily examine massive galaxies for two reasons. The first is that these systems are the easiest to study since they are often the brightest. The second reason is that predictions of galaxy formation models are often most reliable for the most massive systems. In the lambda CDM model these are also the galaxies which are most evolved, and are therefore outstanding test-beds for comparing observations to theory. We discuss below the observations we use to derive the baryonic history of these massive galaxies, and later we combine this information into a summary for how very massive galaxies have formed and developed throughout time. In this review we summarize findings on the merger history of these galaxies, the AGN and star formation history, as well as circumstantial evidence of gas accretion.

2.1. *The Galaxy Merger History*

The major merger history of a sample of very massive galaxies is described in Bluck et al. (2009) who find that while the major merger fraction for $M_\odot > 10^{11}$ $M_\odot$ galaxies at $z < 1.5$ is roughly 10%, at higher redshifts, this increases to 20%-30% at $z = 2 - 3$ (Bluck et al. 2009; Conselice et al. 2009; see Fig. 1). This is roughly consistent with other observations of the merger history using a variety of methods (e.g., Conselice et al. 2008). However, to derive the role of mergers in galaxy formation, it is necessary to calculate the merger rate, that is the number of mergers occurring per unit time as a function of stellar mass. Obtaining an accurate measure of this merger rate requires the time-scale for merging to be known with some certainty (e.g., Bertone & Conselice 2009).

The merger rate for massive galaxies, as derived from simulations of both pairs and morphology, are consistent with each other (Conselice et al. 2009). For these very massive galaxies in major merger pairs, the time-scale is 0.5-1 Gyr, depending on the mass and

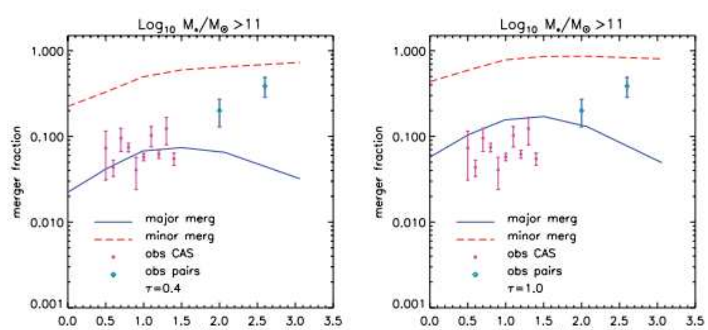

Figure 1. Figure showing the merger history for massive galaxies with stellar masses, $M_\odot > 10^{11}$ $M_\odot$, located at $z < 3$. The points show measurements from different surveys, and the increase in the merger fraction goes as $\sim (1 + z)^3$. The long dashed line shows the predicted major merger history from the Millennium simulation (see Bertone & Conselice 2009). The right and left panel show the range of predicted vs. observed merger fractions using different time-scales (τ).

mass ratio of the merger and the method used to find these mergers (e.g., Lotz et al. 2008). Using this to calculate merger rates, Bluck et al. (2009) find that on average a galaxy will undergo 1.7±0.5 major mergers at $z < 3$. This will roughly double the stellar mass within these galaxies over this time period. The role of minor mergers in building up the masses of galaxies is still largely unknown, but is likely at a similar level (Bluck et al. 2011). Neither minor nor major mergers however can increase the amount of mass within massive galaxies with $M_{\odot} > 10^{11}$ $M_{\odot}$. However, it is possible that these minor mergers are able to increase the sizes of these massive systems, which are well known to be very compact at $z > 1$ (e.g., Buitrago et al. 2008).

2.2. *Star Formation History and Gas Accretion History*

The star formation history of the universe is one of the classical ways to study galaxy evolution. We are now able to trace the star formation history in many ways using many techniques, and we now can examine this as a function of galaxy property and redshift. It is now well established, for example, that the ongoing star formation rate scales with galaxy stellar mass, such that the most massive galaxies are undergoing the highest star formation rates. Systems with $M_{\odot} > 10^{11}$ $M_{\odot}$ have star formation rates between 100 - 500 $M_{\odot}$ year^{-1} on average (Daddi et al. 2007; Bauer et al. 2011). What is interesting about these observations is that the star formation rate for $M_{\odot} > 10^{11}$ $M_{\odot}$ systems has a low scatter for those systems which are star forming. That is, either these massive galaxies are not undergoing star formation at all, or they contain a very high star formation rate, which indicates that the cold gas mass of these systems scale with their stellar mass and galaxy wide star formation events are occurring in tandem.

The increase of stellar mass from star formation can be calculated by integrating the star formation rate for these massive galaxies over time. Doing this, we find that the stellar mass added to galaxies through star formation will roughly double the stellar mass of these systems from $1.5 < z < 3$. This is potentially a very fundamental observation, as it tells us that some process is required to not only keep the star formation active, but also that enough gas is reacquired by galaxies to become replenished in some way for this star formation to continue.

What triggers this star formation is still uncertain in some individual galaxy cases, but we can determine a few likely properties of the star formation and where it originates based on the likely amount of cold gas within these galaxies as a function of time, and

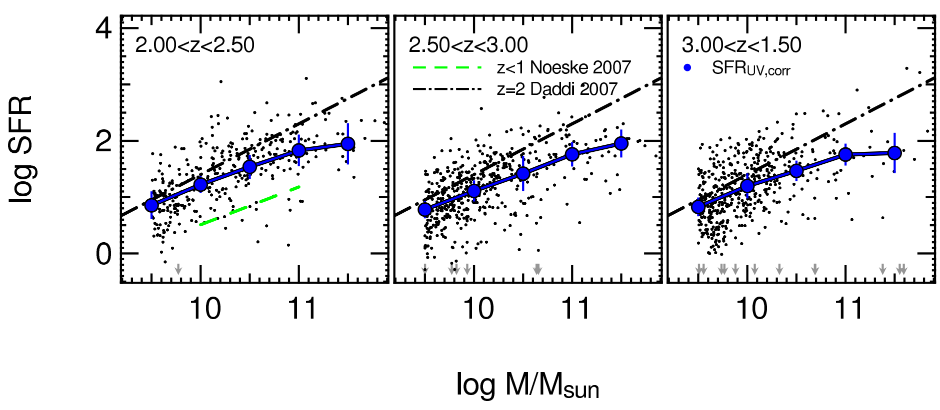

Figure 2. The star formation rate as a function of stellar mass from $z = 1.5$ to $z = 3$ using dust corrected ultraviolet light. The blue line shows the average values for GNS points, while comparisons to previous work is also show (see Bauer et al. 2011).

the observation that the star formation rate for $M_\odot > 10^{11}$ $M_\odot$ galaxies is constant over $1.5 < z < 3$.

At the same time, we know that the cold gas mass density is roughly constant as well, and quite low at 10% for galaxies as massive as our systems with $M_\odot > 10^{11}$ $M_\odot$ (e.g., Erb et al. 2006; Daddi et al. 2010). If the amount of cold gas available to produce new stars is < 10% of the current stellar mass up to $z \sim 3$, then it is very difficult, if not impossible, to produce the amount of observed star formation in these systems without gas replenishment. Even if gas rich minor mergers are occurring it will still be difficult to not only produce this much star formation, but also to keep the cold gas supply constant. One possible method for this is cold gas accretion from the intergalactic medium (e.g., Dekel et al. 2009).

2.3. *Feedback from Central Black Holes*

As is well known, most galaxies have a black hole at their centers whose mass is proportional to that of the galaxy itself (e.g., Haring & Rix 2004). The reason behind this strong relation is not understood completely, nor observationally how the relation between the masses of central black holes and their host galaxies evolve with time. However, we do know that the more massive a central black hole is, the more accretion that black hole has had over time, and therefore the more energy from an active galactic nuclei.

The amount of energy ejected from this AGN into the galaxy is unknown. However, by examining the frequency of AGN over time, we can obtain some estimate for the amount of energy emitted by these forming AGN into the galaxy. As Bluck et al. (2011) show, at any one time, 7.4±2 percent of galaxies with $M_\odot > 10^{10.5}$ $M_\odot$ at $z \sim 2.5$ have an X-ray selected AGN with $L_X > 2.35 \times 10^{43}$. By using the X-ray luminosities of these sources, we can obtain a measure of the central black hole mass times the Eddington ratio (μ) (Fig. 3). Using a measure of these masses times Eddington ratios, we can obtain a minimum amount of energy that these black holes have produced in the form of X-ray AGN since $z = 3$ (Bluck et al. 2011). The result of this is that the amount of energy ejected from the AGN integrated over time, such that the masses of these black holes reach their value today, is roughly a factor of ten times that of the binding energy of the galaxy. While we cannot say how this energy couples with the stars or gas in these galaxies, this amount of energy must have a profound effect on the evolution of these systems.

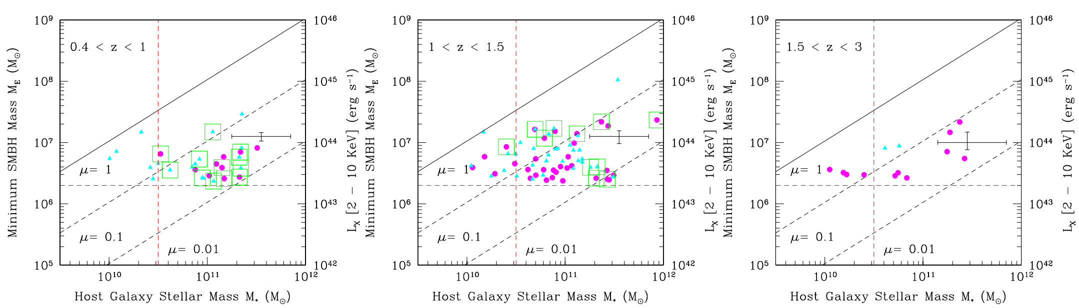

Figure 3. Plots of the evolution of the minimum black hole mass ($M_E = \mu M_{BH}$), based on X-ray luminosities as a function of galaxy stellar mass for a galaxy selected sample up to $z = 3$. Shown are lines for the relation between black hole and galaxy mass at different values of μ (Haring & Rix 2004). Magenta circles are hard X-ray sources and cyan triangles are soft sources with those surrounded by green boxes systems with spectroscopic redshifts (Bluck et al. 2011).

3. Comparison with Theory and Models

The results achieved thus far are in direct competition with models which predict the same quantities. We can test how our observational results of these processes compare with semi-analytical models based on the Millennium simulation (Bertone & Conselice 2009). One initial result of this comparison is shown in Figure 1. This shows how the predicted merger fraction various with redshift from the Millennium simulation compares with various merger fraction measurements from Conselice et al. (2003), Conselice et al. (2008, 2009) and Bluck et al. (2009).

The result of this comparison shows that the simulation results of mergers and the data show quite different merger histories. The measured merger fractions are always higher than the simulation results, showing that perhaps major mergers as measured through structure and through galaxy pairs are more important than what is assumed in models of galaxy formation.

This difference might be related to several effects. The first is that we known that the number densities of massive galaxies are higher at $z > 1$ than that predicted in simulations – demonstrating that galaxy formation is a much faster process that what is predicted in these models (Conselice et al. 2007). The other is that the stellar masses in these models could be off, particularly for satellite galaxies which are quenched in these models, resulting in more minor than major mergers (Bertone & Conselice 2009). In the future, more direct observations will become possible, and these can be used to determine galaxy formation processes largely independently of simulations.

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